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WIND-TUNNEL INVESTIGATION OF CONTROL-SURFACE CHARACTERISTICS

II - A LARGE AERODYNAMIC BALANCE OF VARIOUS NOSE SHAPES WITH A 30-PERCENT-CHORD FLAP ON AN NACA 0009 AIRFOIL

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WIND-TUNNEL INVESTIGATION OF CONTROL-SURFACE CHARACTERISTICS

II - A LARGE AERODYNAMIC BALANCE OF VARIOUS NOSE SHAPES WITH A 30-PERCENT-CHORD FLAP ON AN NACA 0009 AIRFOIL

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SUMMARY

Tests have been made of an NACA 0009 airfoil with a 30-percent-chord flap having a 49.5-percent flap-chord balance with various nose shapes and two gaps. The results have been presented in the form of aerodynamic section characteristics.

These results indicated the flap to be overbalanced when deflected, regardless of nose shape. There was only a slight change in hinge moment with angle of attack. A blunt-nose shape gave the greatest reductions in hinge moment and the smallest increment of drag over that of a plain airfoil. The small gap investigated affected the aerodynamic characteristics only slightly.

A method has been proposed for reducing the control forces to any desired value while, at the same time, markedly increasing the lift effectiveness of the airfoil-flap combination over that of a plain flap of the same chord. In addition, the flap can be made to float against the relative wind thereby causing the stability with controls free to exceed that with controls fixed. These results are accomplished by using a differentially operated balancing tab on an overbalanced flap to increase both the lift and the hinge moment of the flap.

INTRODUCTION

Because of the increasing size and speed of modern airplanes, it has become increasingly necessary to reduce the hinge moments on the control surfaces and thus to reduce the forces on the control stick. In an effort to solve this problem, the NACA has initiated an extensive investigation of the aerodynamic characteristics of control surfaces in order to provide data for design purposes and to determine the type of flap arrangement best suited for use as a control surface. Because a conventional control surface is merely a flap on an airfoil, these two terms are used synonymously.

As a part of this investigation, some effects of flap nose shape and gaps on a typical horizontal tail of finite span were determined in the full-scale wind tunnel and are reported in reference 1. The more fundamental part of the investigation, however, is being made in two-dimensional flow. The first part of the two-dimensional flow investigation was the determination of the section characteristics of airfoil-flap combinations using plain flaps of various sizes and with sealed gaps. (See references 2, 3, and 4.) The data presented in these references have been analyzed, and parameters for determining the characteristics of a thin symmetrical airfoil with a plain flap of any size chord and with the gap at the flap nose sealed are given in reference 5. The effects of gap size on the characteristics of a thin airfoil with a plain flap are reported in reference 6.

The tests reported herein were made to provide section data for an airfoil having a flap with a large overhang and to determine the effects of the shape of the nose of this overhang. The terms "balance" and "overhang" are used synonymously to indicate the portion of the movable surface ahead of the hinge axis.

APPARATUS AND MODEL

The tests were made in the NACA 4- by 6-foot vertical tunnel (reference 7) modified, as described in reference 2, for force tests of models in a two-dimensional flow. A three-component balance system has been installed in the tunnel in order that force test measurements of lift, drag, and pitching moment may be made. The hinge moments of the flap and tab were measured with special torque rod balances built into the model.

The 2-foot-chord by 4-foot-span model was made of laminated mahogany to the NACA 0009 profile. It was equipped with a balanced flap having a chord 30 percent of the airfoil chord and a plain tab having a chord 20 percent of the flap chord. The flap chord is measured from the flap hinge axis to the trailing edge of the airfoil. The aerodynamic balance, measured from the flap hinge axis to the nose of the movable surface, consisted of an overhang that was 49.5 percent of the flap chord. The overhang was made with a blunt-, a medium-, and a sharp-nose shape (fig. 1 and table I). The gap was fixed at 0.15 percent of the airfoil chord by removable airfoil tail blocks, and it was also sealed with grease. The tab was made of brass and its gap was fixed at 0.10 percent of the airfoil chord.

The installation of the model in the tunnel was similar to that of references 2, 3, and 4. Because the model completely spanned the tunnel, two-dimensional flow was approximated. The flap and the tab deflections were set by friction clamps on the torque rods that were used in measuring the hinge moments.

TESTS

The tests were made at a dynamic pressure of 15 pounds per square foot which corresponds to a velocity of about 76 miles per hour at standard sea-level conditions. The test Reynolds number was 1,430,000 and the effective Reynolds number of the tests was approximately 2,760,000. (Effective Reynolds number = test Reynolds number × turbulence factor. The turbulence factor for the 4- by 6-ft vertical tunnel is 1.93.)

The flap deflections were set at 5° increments, and with the blunt nose and sealed gap, tests also were made at 1°, 2°, and 3° flap deflections. With sealed gap the maximum flap deflection tested was limited to 15° or 20°, depending on the flap nose shape, because of difficulties in maintaining the gap seal. With the gap unsealed, flap deflections from 0° to 30° were tested. The tab was tested at 0° for all nose shapes, and with the blunt nose and sealed gap, tab tests were made with the tab deflected 5°, 10°, and 15°. For each flap and tab setting, force tests were made throughout the angle-of-attack range in 2°

increments from the negative stall to the positive stall. Near the stall, however, 1° increments were taken. Lift, drag, and pitching moment of the airfoil and hinge moment of the flap were measured.

RESULTS AND DISCUSSION

Symbols

The coefficients and symbols used in this paper are defined as follows:

c_l airfoil section lift coefficient $\left(\frac{l}{qc}\right)$

c_{d_o} airfoil section profile-drag coefficient $\left(\frac{d_o}{qc}\right)$

c_m airfoil section pitching-moment coefficient about the quarter-chord point of airfoil $\left(\frac{m}{qc^2}\right)$

c_{h_f} flap section hinge-moment coefficient $\left(\frac{h_f}{qc_f^2}\right)$

where

l airfoil section lift

d_o airfoil section profile drag

m airfoil section pitching moment about quarter-chord point of airfoil

h_f flap section hinge moment

c chord of basic airfoil with flap and tab neutral

c_f flap chord

q dynamic pressure

α_o angle of attack for an airfoil of infinite span

δ_f flap deflection with respect to airfoil

δ_t tab deflection with respect to flap

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Precision

The accuracy of the data is indicated by the deviation from zero of lift and moment. The maximum error in effective angle of attack at zero lift appears to be about $\pm 0.2^\circ$. Flap deflections were set to within $\pm 0.2^\circ$. Tunnel corrections, experimentally determined in the 4- by 6-foot vertical tunnel, were applied to lift only. The hinge moments, therefore, are probably slightly higher than would be obtained in free flight, but the values presented are considered to be conservative. The increments of drag should be reasonably independent of tunnel effect, although the absolute drag is subject to an unknown correction. Inaccuracies in the section data presented are thought to be negligible relative to inaccuracies that will be incurred in the application of the data to finite airfoils.

Discussion

The desirability of reducing the hinge moments of control surfaces is obvious, but the method of doing so must be carefully selected in order that the lift and the free-floating characteristics of the flap will not be rendered unsatisfactory. It is considered desirable to make the free-floating angle of the flap equal to zero or even to have a slightly positive value at positive angle of attack so that the flap will float against the relative wind. This means that the parameter $\left(\frac{\partial c_h}{\partial \alpha_o}\right)_{\delta_f}$ (reference 5) must be made zero or slightly positive. At the same time, $\left(\frac{\partial c_h}{\partial \delta_f}\right)_{\alpha_o}$ must be made as small a negative value as possible in order to reduce the hinge moments without producing overbalance. While the hinge moments are being reduced in this manner, the effectiveness of the flap in producing lift should be made as great as, or greater than, that of a plain flap of the same chord. No appreciable increment of drag over that of a plain flap can be tolerated at low flap deflections used for trim. With these standards established, the analysis of the characteristics of a flap having a $0.495c_f$ overhang can more easily be made.

Lift

The tests indicate that with a sealed gap the slope of the lift curve, $\frac{\partial c_l}{\partial \alpha_o}$, was 0.099 with the sharp nose flap, 0.101 with the medium nose flap, and 0.102 with the blunt nose flap (figs. 2, 3, and 4). When the gap at the flap nose was 0.0015c, the slope of the lift curve for all three nose shapes was 0.098. Corrections for aspect ratio are presented in reference 5.

With a sealed gap, the effectiveness of the flap in producing lift, for all three flap nose shapes, was practically identical with that of a plain flap of the same chord (reference 6). The flap with the medium nose was, however, slightly better than either the blunt or sharp nose flaps, which two shapes had about the same effectiveness.

The curves of figures 2, 3, and 4 indicate that with a 0.0015c gap, the flap with a blunt nose was slightly more effective in producing lift than the flap with a medium nose, but with the medium nose the flap maintained its effectiveness to higher flap deflections and consequently higher lift coefficients. The sharp nose flap had about the same lift effectiveness as the medium nose flap and about the same range of effectiveness as the blunt nose flap. Consequently, as far as lift characteristics were concerned, the flap with the medium nose appeared to be the most desirable. Although a gap of 0.0015c appears to give slightly better results than a sealed gap, it should be realized that this gap is smaller than it is generally practicable to use on an airplane. In this investigation no tests have been made using a larger gap and the data on gap effect are, therefore, not conclusive.

Hinge Moment of Flap

Figures 2, 3, and 4 present the hinge-moment coefficients of the flap as a function of lift coefficient at constant flap deflection for the various nose shapes and

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gaps. Cross plots, similar to figure 5, giving hinge-moment coefficient as a function of angle of attack and also of flap deflection are more convenient for analysis, but these curves, of course, will be affected by aspect ratio. Reference 5 discusses fully the manner in which aspect ratio affects hinge-moment characteristics. This discussion indicates that $\left(\frac{\partial c_h}{\partial \alpha_o}\right)_{\delta_f}$ will always decrease with decrease in aspect ratio except when its value is zero. For this case, because theory shows there can be no change in the value of $\left(\frac{\partial c_h}{\partial \alpha_o}\right)_{\delta_f}$, there can be no change in the value of $\left(\frac{\partial c_h}{\partial \delta_f}\right)_{\alpha_o}$ with aspect ratio. If for infinite aspect ratio $\left(\frac{\partial c_h}{\partial \alpha_o}\right)_{\delta_f}$ and $\left(\frac{\partial c_h}{\partial \delta_f}\right)_{\alpha_o}$ are of opposite sign, $\left(\frac{\partial c_h}{\partial \delta_f}\right)_{\alpha_o}$ will increase in magnitude as the aspect ratio is decreased. If, however, these parameters have the same sign, $\left(\frac{\partial c_h}{\partial \delta_f}\right)_{\alpha_o}$ will always decrease as the aspect ratio is decreased. In some cases the value of $\left(\frac{\partial c_h}{\partial \delta_f}\right)_{\alpha_o}$ may even pass through zero and change sign as the magnitude of $\left(\frac{\partial c_h}{\partial \alpha_o}\right)_{\delta_f}$ is changed by aspect ratio. It is important that these facts be established because, with a $0.495c_f$ overhang, the slopes of these parameters are very small and the signs are critical.

A $0.495c_f$ overhang on a 0.30c flap produced overbalance through some range of flap deflection regardless of the nose shape and gap (figs. 2, 3, and 4). Overbalance occurred first at high flap deflections and high negative angles of attack for all nose shapes and was slightly more pronounced with a 0.0015c gap than with a sealed gap. As the bluntness of the flap nose increased, the flap deflection at which overbalance first occurred became less, and the magnitude of the overbalancing moment was greater.

When flow separation occurred over the flap, there was a sudden change in the hinge moment to large negative values indicating a rearward movement of the center of pressure.

Drag

At zero angle of attack with flap neutral, the flap with a sharp nose gave an increase in profile-drag coefficient, Δc_{d_0}, of 0.0042 over that of a plain airfoil. With the medium nose the increment was 0.0015, whereas with the blunt nose the increment was not measurable. Because the drag of control surfaces at high flap deflections is of relatively minor importance and the absolute value of the drag coefficient for these data is in error by an unknown tunnel correction, no drag curves have been given. For the blunt nose, however, the increments of drag caused by low flap deflections such as may be necessary for trim changes at high speed are given in figure 6 for several angles of attack. The blunt nose seems to be the only one which was satisfactory as far as drag is concerned.

Pitching Moment

With the blunt- and the medium-flap nose shapes, the rate of change of airfoil section pitching-moment coefficient with lift coefficient at zero flap deflection, $\left(\frac{\partial c_m}{\partial c_l}\right)_{\delta_f}$, is about 0.010 (figs. 2 and 3). This slope indicates that the aerodynamic center was at the 24-percent-chord point, which is in agreement with the results of tests of reference 8. For the sharp nose the slope of the pitching-moment-coefficient curve was slightly less (fig. 4). The airfoil pitching-moment coefficients were unaffected by the presence of a small gap at the flap nose.

Effect of Differential Balancing Tab

From the discussion of the hinge-moment characteristics, it is apparent that because of overbalance, a flap with $0.495c_f$ overhang cannot be used without modifications.

It is possible, however, to use in conjunction with this flap arrangement a trailing-edge tab, deflected in the same direction as the flap, in order to overcome the overbalance of the flap.

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Accordingly, tests were made to determine the effect of a tab deflected with the flap. Figure 7 gives the increments of lift coefficients and flap hinge-moment coefficients caused by deflection of a $0.205c_f$ plain tab at several angles of attack and flap deflections. The increments were determined for the flap with a blunt nose and sealed gap. The curves indicate that on a flap with a $0.49c_f$ overhang, a tab is just about as effective in producing lift but only approximately 75 percent as effective in increasing hinge moments as it is when on a plain flap. These results are logical because of the manner in which a flap or tab affects the pressure distribution over an airfoil.

The tab characteristics having been determined, calculations were made to determine the tab deflections required to give desirable hinge-moment characteristics to a flap with a $0.495c_f$ blunt-nose overhang and with sealed gap. The curve of tab deflection as a function of flap deflection given in figure 8 was selected to make $\left(\frac{\partial c_h}{\partial \delta_f}\right)_{\alpha_0}$ equal to zero at 0° angle of attack. The differential tab linkage will change the flap hinge-moment characteristics from those of figure 5 to those of figure 8, which is a cross plot of actual test data. The curves of figure 8 show that except for high positive angles of attack with large flap deflections the hinge moments of the flap can be trimmed out with a small deflection of the trim tab. At a large flap deflection and a high positive angle of attack, which is comparable to a critical condition for rudders, separation caused the flap overhang to lose its balancing effectiveness which resulted in an increase in hinge-moment coefficient. This difficulty can be avoided, however, by using a flap of sufficiently large flap-chord ratio, $\frac{c_f}{c}$, to secure adequate control without reaching critical deflections.

Thus by means of a large aerodynamic balance used in conjunction with a differentially operated balancing tab, the hinge-moment parameters may be independently varied. By making $\left(\frac{\partial c_h}{\partial \alpha_o}\right)_\delta$ positive and $\left(\frac{\partial c_h}{\partial \delta}\right)_{\alpha_o}$ slightly negative, the flap can be made to float against the relative wind when free and yet not be overbalanced when deflected. This floating tendency of the flap will cause the airplane stability with controls free to exceed that with controls fixed.

Figure 9 compares the lift effectiveness of the flap having both a $0.495c_f$ blunt-nose overhang and a differential balancing tab with that of a plain flap of the same chord (reference 6). As expected, the tab deflected with the balanced flap gave considerably greater lift effectiveness than did the plain flap.

Thus it appears that a differential balancing tab used in conjunction with an overbalanced flap can be made to give very desirable lift and hinge-moment characteristics. With stick force and free-control stability regulated in the manner already indicated, flaps having very large ratios of flap chord to airfoil chord and operating at low deflections can be used to great advantage for control surfaces.

CONCLUDING REMARKS

The results of the tests showed that a flap with 49.5-percent overhang was aerodynamically overbalanced when deflected regardless of nose shape. The large amount of overhang reduced the slope of the curve of hinge moment against angle of attack to practically zero. The flap effectiveness in producing lift was about the same as for the unbalanced flap of the same chord. The small gap tested had little effect on any of the characteristics. The smallest increment in drag was obtained with the blunt-nose shape.

A tab deflected in the same direction as the flap in order to increase both the lift and the hinge moment of an overbalanced flap shows promise of being a very satisfactory arrangement for reducing stick forces and improving free-control stability.

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TABLE I

Stations and Ordinates for Medium Nose

Station (percent c)	Ordinate (percent c)
0	0
.35	.88
.85	1.26
1.85	1.68
2.85	1.96
3.85	2.15
4.85	2.30
5.85	2.42
6.85	2.52
7.85	2.58
8.85	2.64
9.85	2.66
10.85	2.70
11.85	2.71
12.85	2.72
13.85	2.73
14.85	2.72
15.85	2.63
16.85	2.55
19.50	2.40
Fair to NACA 0009 profile to trailing edge	
Nose radius = 1.23 percent c	

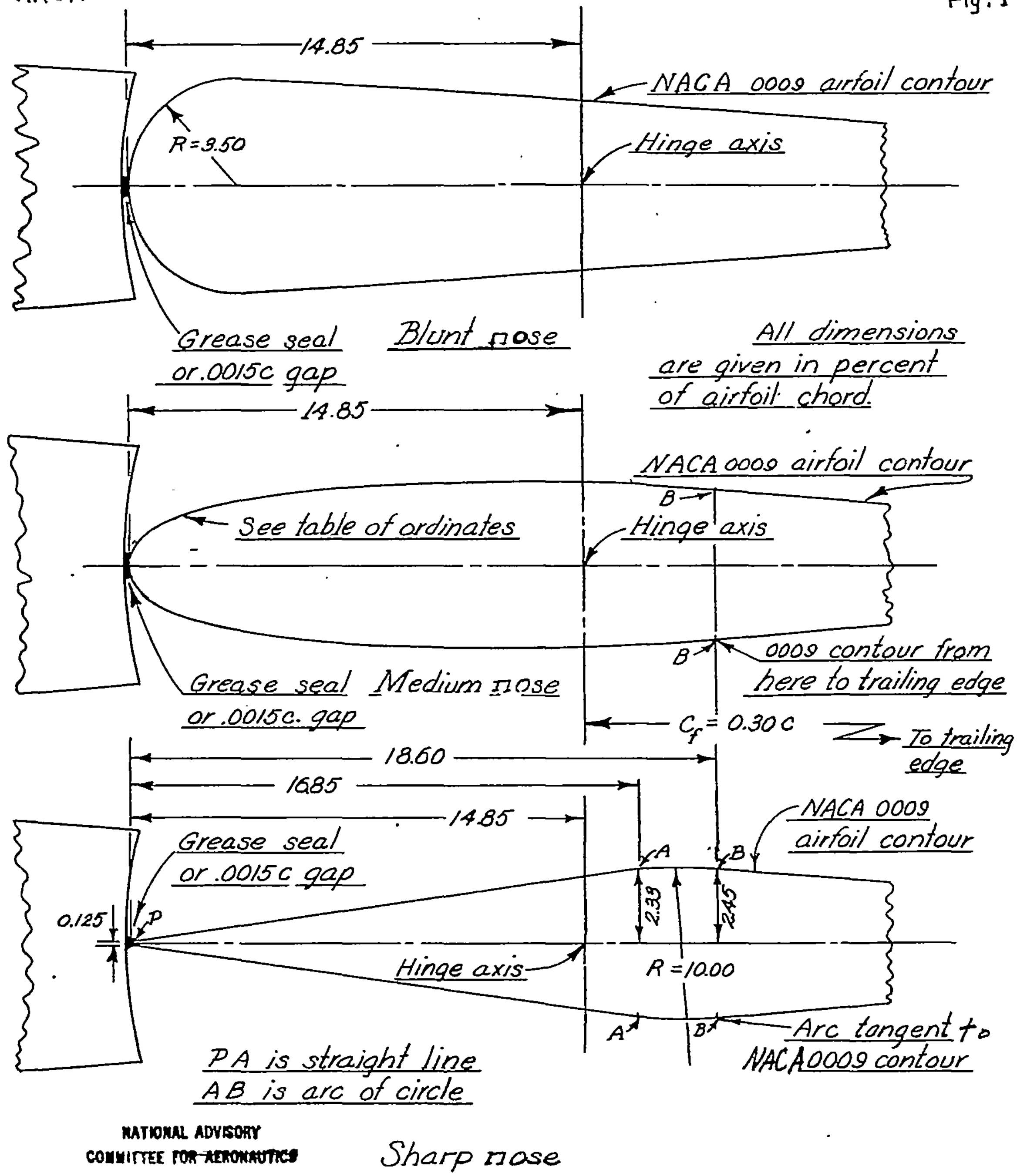
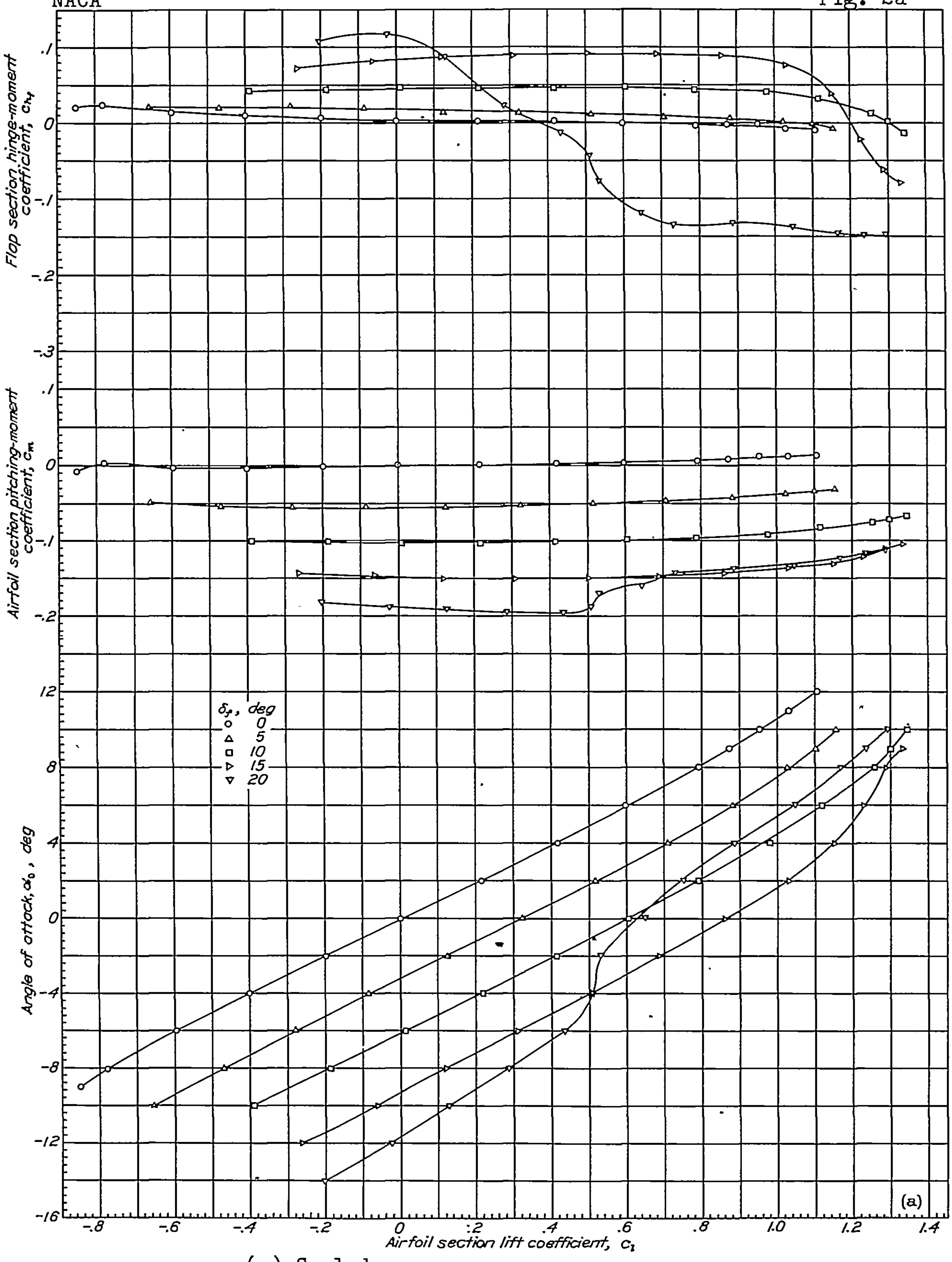


FIGURE 1.–Nose shapes for a 0.30c flap with 0.495 c_f overhang on an NACA 0009 airfoil.



(a) Sealed gap.

Figure 2a,b.- Section aerodynamic characteristics of an NACA 0009 airfoil with a 0.30c flap having a 0.495c_f overhang with blunt nose.

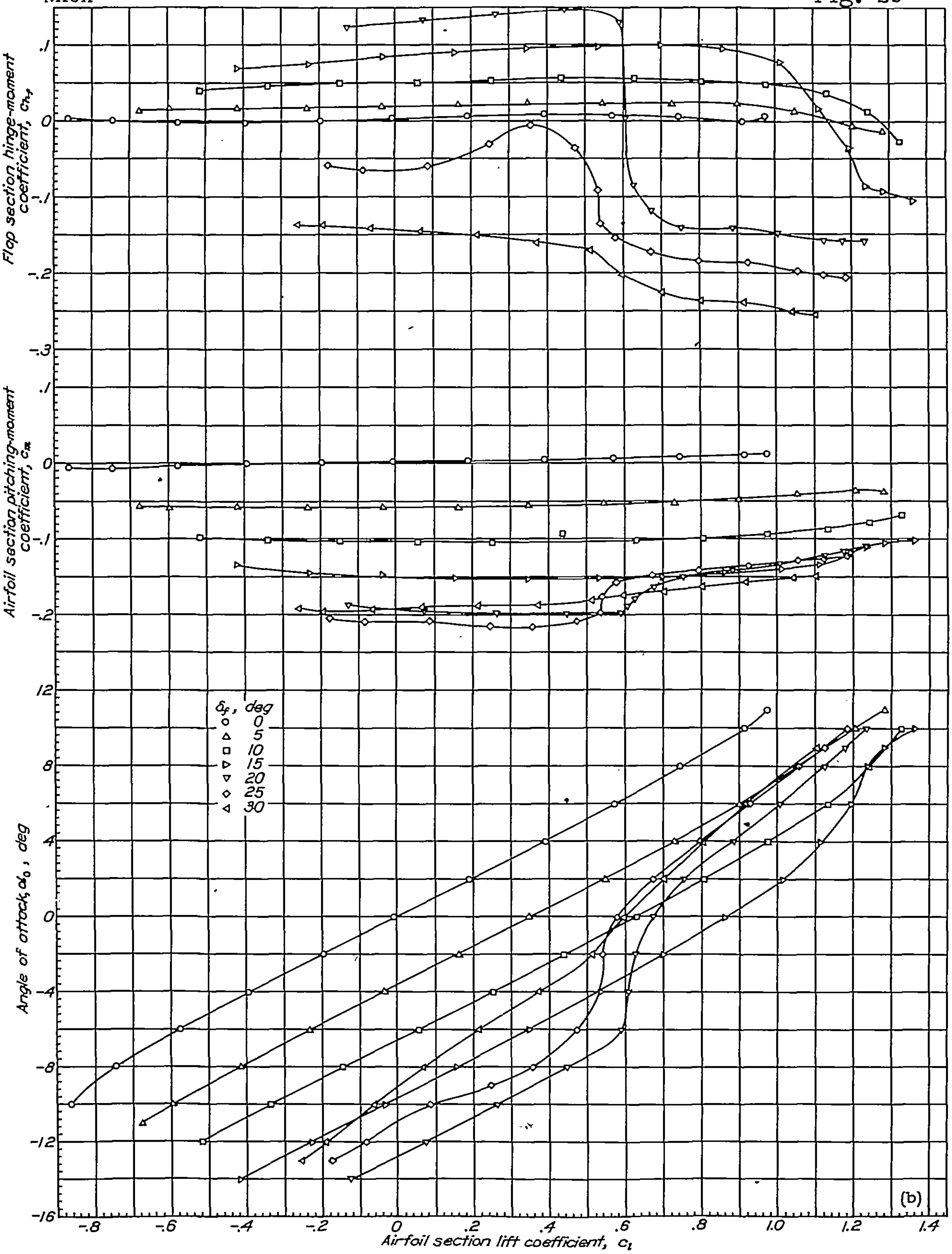
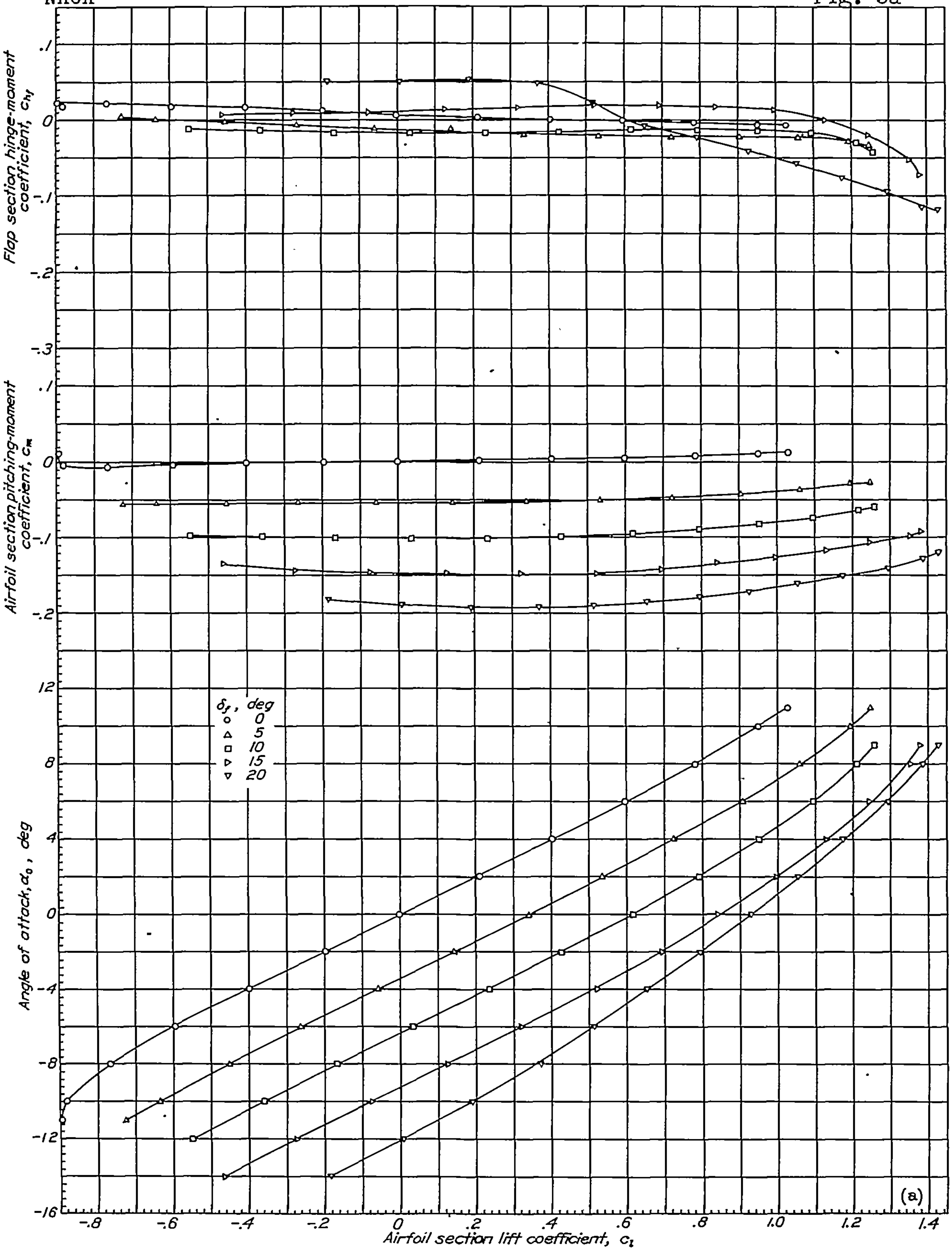


Figure 2(b) 0.0015c gap.



(a) Sealed gap.

Figure 3a,b.- Section aerodynamic characteristics of an NACA 0009 airfoil with a 0.30c flap having a 0.495c_f overhang with medium nose.

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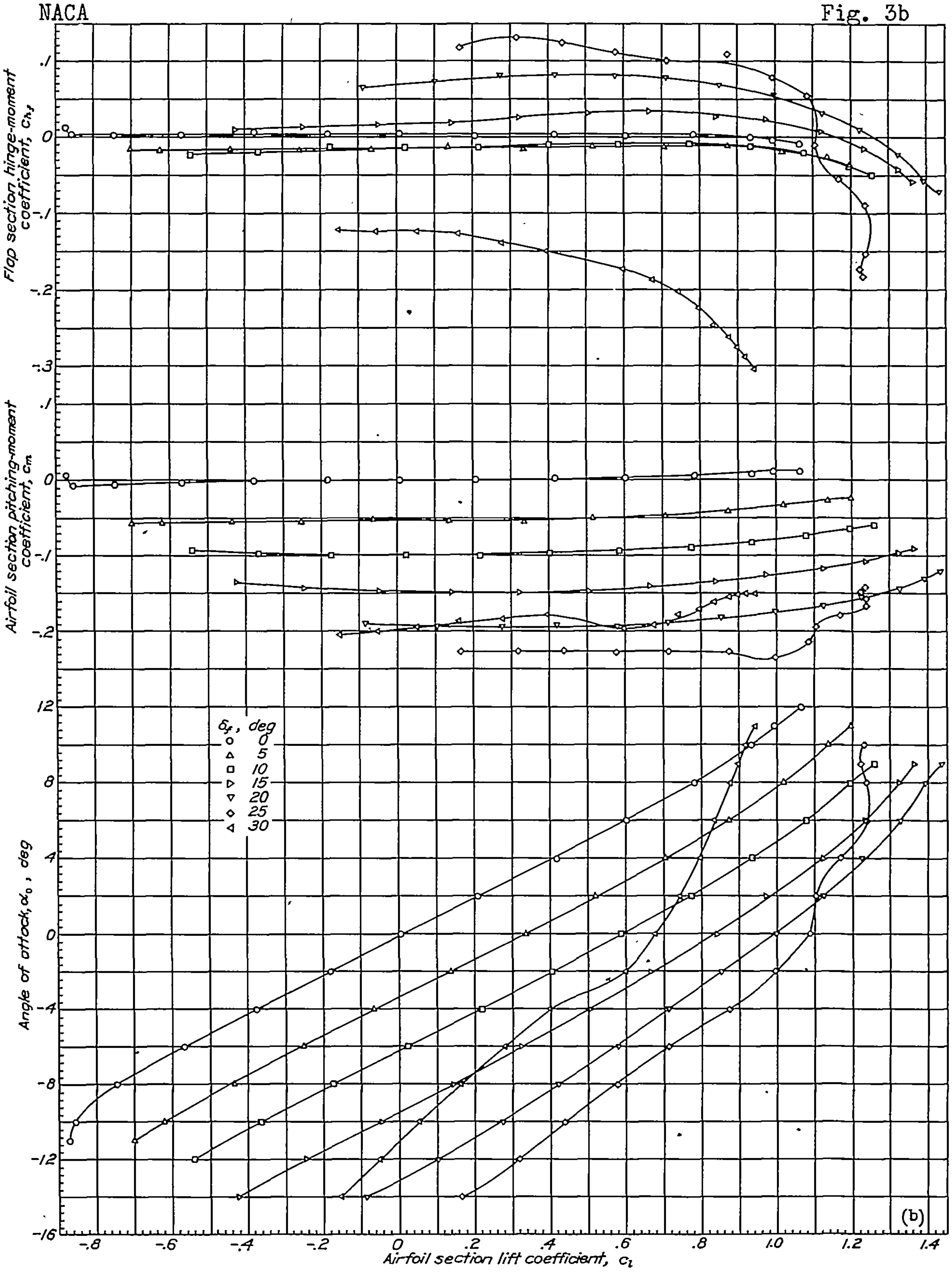

Figure 3(b) 0.0015c gap.

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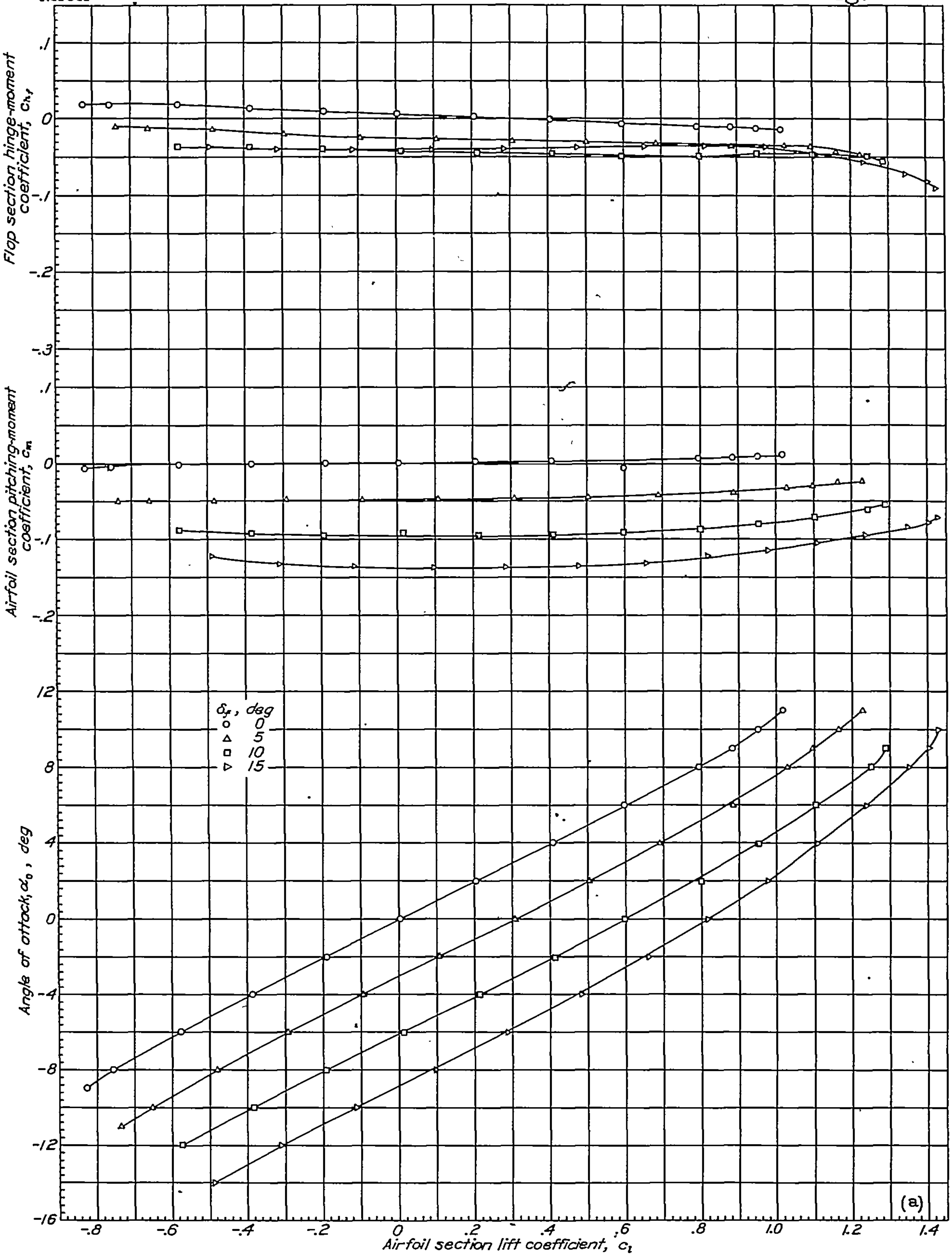

(a) Sealed gap.

Figure 4a,b.- Section aerodynamic characteristics of an NACA 0009 airfoil with a 0.30c flap having a 0.495c_f overhang with sharp nose.

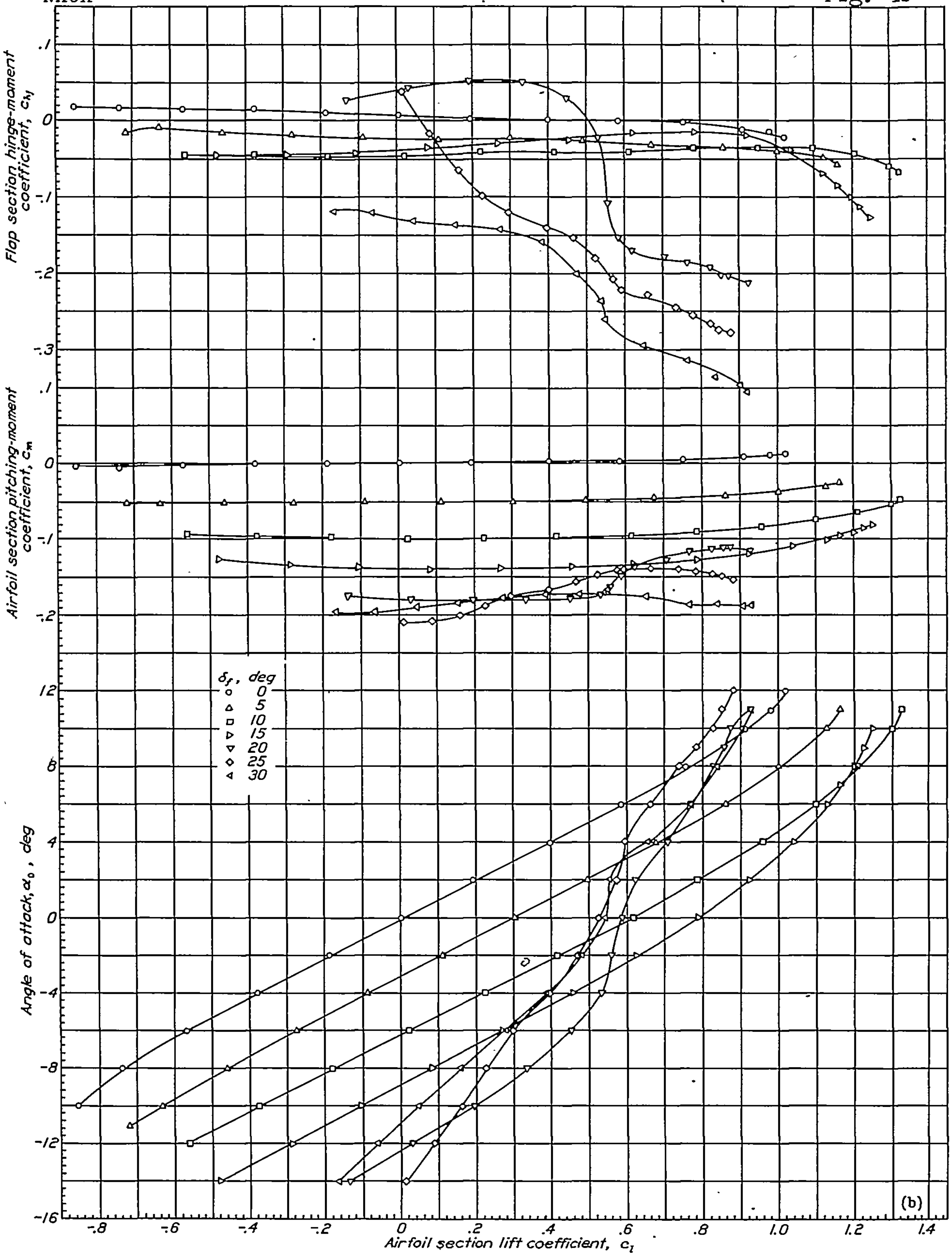

Figure 4(b) 0.0015c gap.

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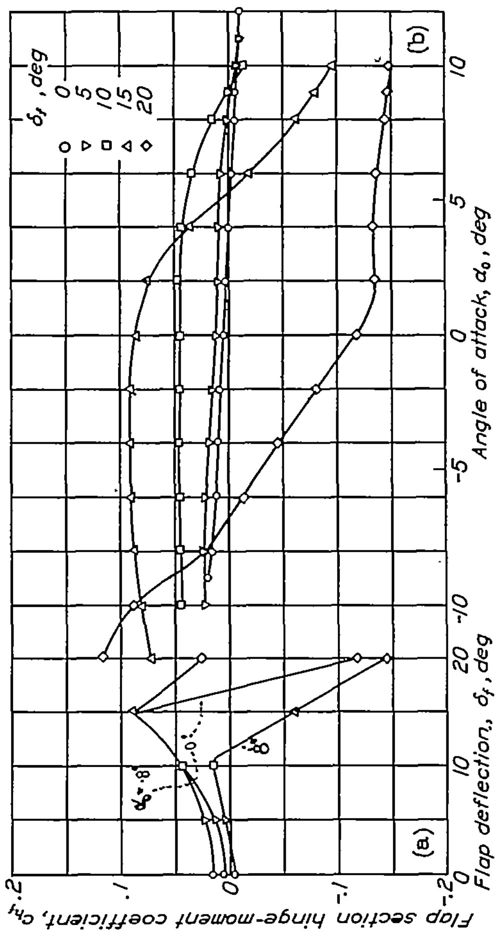

Figure 5. Hinge moment characteristics of a 0.30c flap with 0.495cf overhang, blunt nose, and sealed gap. NACA 0009 airfoil.

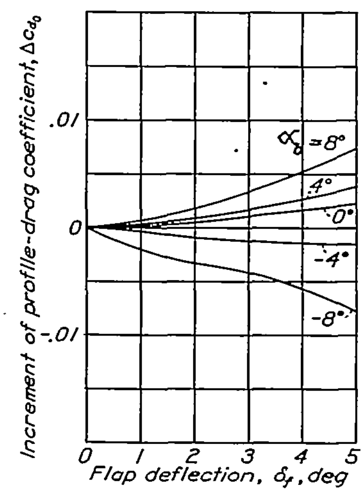

Figure 6.- Increment of profile-drag coefficient caused by flap deflection. Blunt nose, sealed gap, 0.495cf overhang.

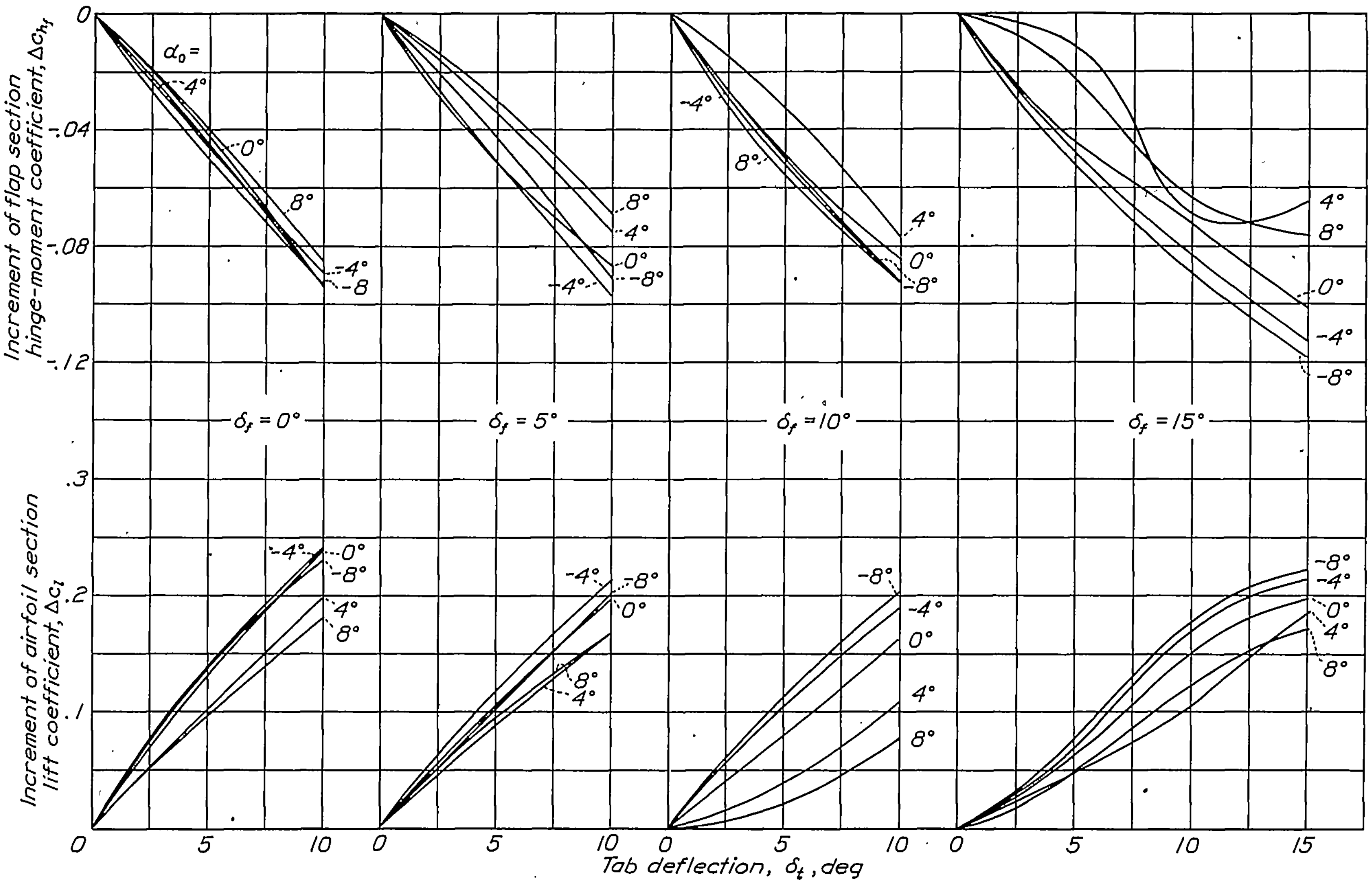

Figure 7.- Increments of airfoil section lift coefficient and flap section hinge-moment coefficient caused by deflection of a 0.20c_f plain tab. Blunt nose overhang and sealed gap.

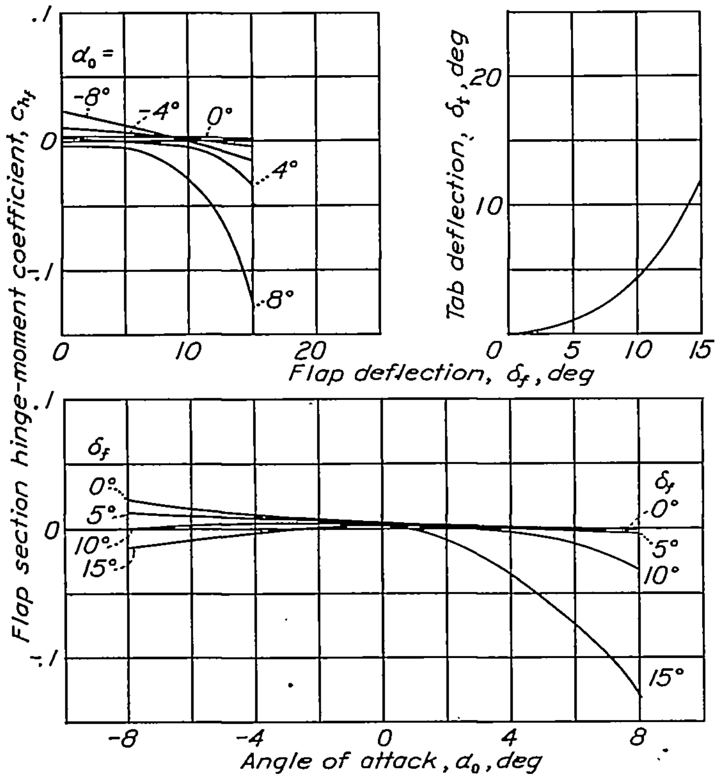

Figure 8.- Hinge-moment characteristics of a 0.30c flap having 0.495c_f overhang, blunt nose, and sealed gap and a 0.20c_f differential balancing tab. NACA 0009 airfoil.

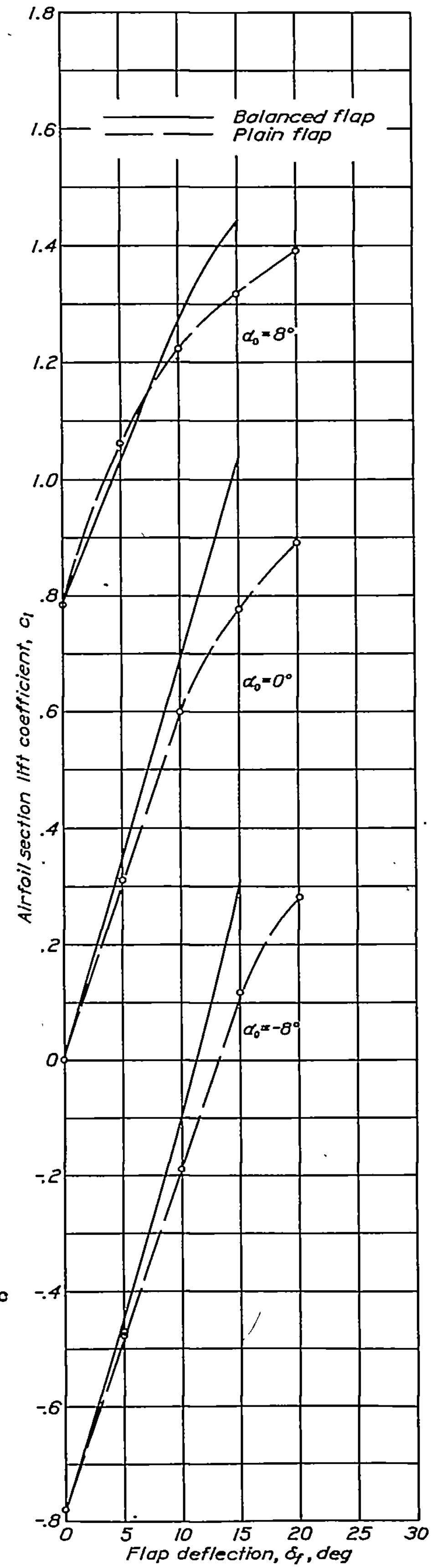

Figure 9.- Lift characteristics of a 0.30c plain flap and a 0.30c flap with a 0.495c_f blunt nose overhang and a 0.20c_f differential balancing tab. Sealed gaps. NACA 0009 airfoil.

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